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Selecting Suitable Sites for Animal Waste Application Using a Raster GIS

BADRI B. BASNET*
ARMANDO A. APAN
STEVEN R. RAINE
Faculty of Engineering and Surveying
University of Southern Queensland
Toowoomba, Queensland 4350, Australia

ABSTRACT / Rapid growth of intensive animal industries in southeast Queensland, Australia, has led to large volumes of animal waste production, which posses serious environmental problems in the Murray Darling Basin (MDB). This study presents a method of selecting sites for the safe application of animal waste as fertiliser to agricultural land. A site suitability map for the Westbrook subcatchment within the MDB was created using a geographic information system (GIS)-based weighted linear combination (WLC) model. The factors affecting the suitability of a site for animal waste application were selected, and digital data sets derived from up to 1:50,000 scale maps were acquired. After initial preprocessing, digital data sets were clipped to the size of the delineated subcatchment boundary producing input factors. These input factors were weighted using the analytical hierarchy process (AHP) that employed an objectives-oriented comparison (OOC) technique to formulate the pairwise comparison matrix. The OOC technique, which is capable of deriving factor weight independently, formulated the weight derivation process by making it more logical and systematic. The factor attributes were classified into multiple classes and weighted using the AHP. The effects of the number of input factors and factor weighting on the areal extent and the degree of site suitability were examined. Due to the presence of large nonagricultural and residential areas in the subcatchment, only 16% of the area was found suitable for animal waste application. The areal extent resulting from this site suitability assessment was found to be dependent on the areal constraints imposed on each input factor, while the degree of suitability was principally a function of the weight distribution between the factors.

Intensive animal industries (IAI) are concentrated production facilities that take economic advantage by managing large numbers of animals in a confined area. In recent years, there has been a significant increase in the number and size of IAI in the Condamine region of the Murray Darling Basin (MDB) in southeast Queensland, Australia. Wastes generated in IAI (e.g., dairy, feedlot, piggery, and poultry) are usually stored near the production facilities prior to biological processing and/or application to agricultural fields as fertilizer. However, improperly stored and/or disposed waste may contribute to agricultural nonpoint source (NPS) pollution causing serious environmental problems, including eutrophication and toxic blue-green algae blooms.

Agricultural NPS pollution has become a serious environmental threat in the Murray Darling River System (Herath 1997), where the world's largest toxic riverine algal bloom was recorded in October 1991 (Young and others 1996), and the severity and frequency of algal blooms is increasing (Scarsbrick 1995). Runoff from fields fertilized with animal manure has been one of the major sources of agricultural NPS pollution (Langford and others 1990).

*Author to whom correspondence should be addressed.

KEY WORDS: Intensive animal industries; Animal waste; Objectives oriented comparison; Analytical hierarchy process, Site suitability; Weighted linear combination model; Geographic information system

Using Animal Waste as Fertiliser

Animal waste includes livestock and poultry manure, bedding, litter, and other waste materials such as wastewater, feedlot runoff, silage juices, and wasted feed (Hammond 1994). This waste has historically been a major source of plant nutrients in traditional agricultural systems worldwide. Although chemical, biological, and engineering methods of waste use are available (e.g., composting, biogas generation and processing for refeeding), application as manure to cropland remains the most common and often least expensive method of animal waste utilization (He and Shi 1998). Fertilizing agricultural fields with animal manure recycles the nutrients (Couillard and Li 1993), supports crop production (Hammond and others 1994), and enhances the physical and chemical properties of the soil (He and Shi 1998). However, inappropriate storage, disposal, and/or use of animal waste can result in runoff of nutrients, pathogens and oxygen demanding substances that can create major environmental problems (Camberato and others 1990).

One of the most serious environmental concerns is the runoff loss of nutrients from the fields fertilized with animal manure. Continuous application of animal waste has been found to result in soil nutrient buildup (Liu and others 1998), increased nutrient runoff (Davies and others 1997), and water quality deterioration (Mostaghimi and others 1992) due to increases in nitrogen, phosphorus, and algal production (Couillard and Li 1993).

Technological solutions to reduce NPS pollution from agricultural land fertilized with animal waste include identification of better soil and cropping management practices, timeliness in application, improved application methods, and optimum application rates (Overcash and others 1983). However, while technological solutions may help to reduce pollution, the main determinants of environmental problems are likely to be the site characteristics (e.g., location, soil, topography, land cover, land use, and proximity to watercourses). Hence, agricultural land fertilized with animal waste may allow leaching and/or runoff of pollutants into ground and surface water, become a source of bad odor to the community, and/or may be uneconomic if that field is unsuited for animal waste application. Selection of a suitable site to satisfy these socioeconomic and environmental requirements should, in fact, precede all other technological investigations. So far, there have been few scientific investigations into the socioeconomic and environmental assessment of agricultural fields for their suitability in animal waste application.

GIS and Site Suitability

Site selection is a spatial problem that requires inputs of large volumes of biophysical, environmental, and sociopolitical data. A geographic information system (GIS) is a tool for entering, storing, manipulating, analyzing and displaying large volumes of spatial data (Congalton and Green 1992). Recent advancements in GIS have developed techniques to select, rank and map sites that are suitable (or unsuitable) for a specific purpose (Davis 1996). A GIS-based site-selection procedure is potentially useful to manage agricultural NPS pollution through the identification and mapping of sites where the application of animal waste is less likely to produce NPS pollution of riverine flows. Site suitability analysis involves overlaying graphically (or combining databases) of more than one coverage to locate suitable spatial (or attribute) conditions (Davis 1996). Vector-based methods are most commonly applied to identify suitable sites for various purposes. For example, vector GIS has been used to identify dump sites in Malyasia (Yagoub and Buyong 1998), landfill sites in the United States (Herzog 1999) and Turkey (Basagaoglu and others 1997), solid waste disposal sites in the Philippines (Cruz 1993), and animal waste application sites in Australia (Basnet and others 2000). Selecting sites using a raster-based method in conjunction with the weighted linear combination (WLC) model has become popular in recent years. The WLC is a mathematical model available for delineating and ranking suitable sites for specific purposes (Hopkins 1977). This model has been used to identify and rank suitable sites for land application of wastewater (Hendrix and Buckley 1992), land filling (Siddiqui and others 1996), and manure application (Jain and others 1995). However, no work has been conducted to evaluate the sensitiveness of inputting constrained and weighted factors into the WLC model while determining the areal extent and the degree of site suitability for animal waste application using raster GIS.

Objective and Hypotheses

It is apparent from the literature that the focus in the past has been mainly in the safe disposal of municipal waste. The application of animal waste as fertilizer in agricultural fields has not been under environmental scrutiny until recently. The increasing occurrence of toxic blue-green algae blooms in many parts of the world, however, has prompted investigations into agricultural NPS pollution to which animal waste is one of the major contributors (Herath 1997).

Environmentally safe recycling of animal waste in agricultural fields has thus become critical to reduce agricultural NPS pollution. Safe recycling of animal waste involves site-specific application, which in turn requires selecting suitable sites and assessing their degree of suitability from socioeconomic, agricultural, and environmental perspectives. In selecting suitable sites using a WLC model, the input factors are selected, constrained (i.e., unsuitable areas blacked out), standardized (i.e., factor attributes classified and ranked), and weighted (i.e., assigned weights to the factor) before combining them linearly. The number of input factors, the constraints imposed by each input factor, and the weights assigned to the input factors can be expected to play an important role on the areal extent and the degree of suitability. However, the effect of the number of input factors, factor constraints, and the weight distribution between factors on the areal extent and the degree of site suitability are not yet fully understood. Therefore, the objectives of this study were to use a WLC model within a raster GIS to: (1) identify and map the agricultural areas that are potentially suitable for animal waste application; (2) evaluate the de-

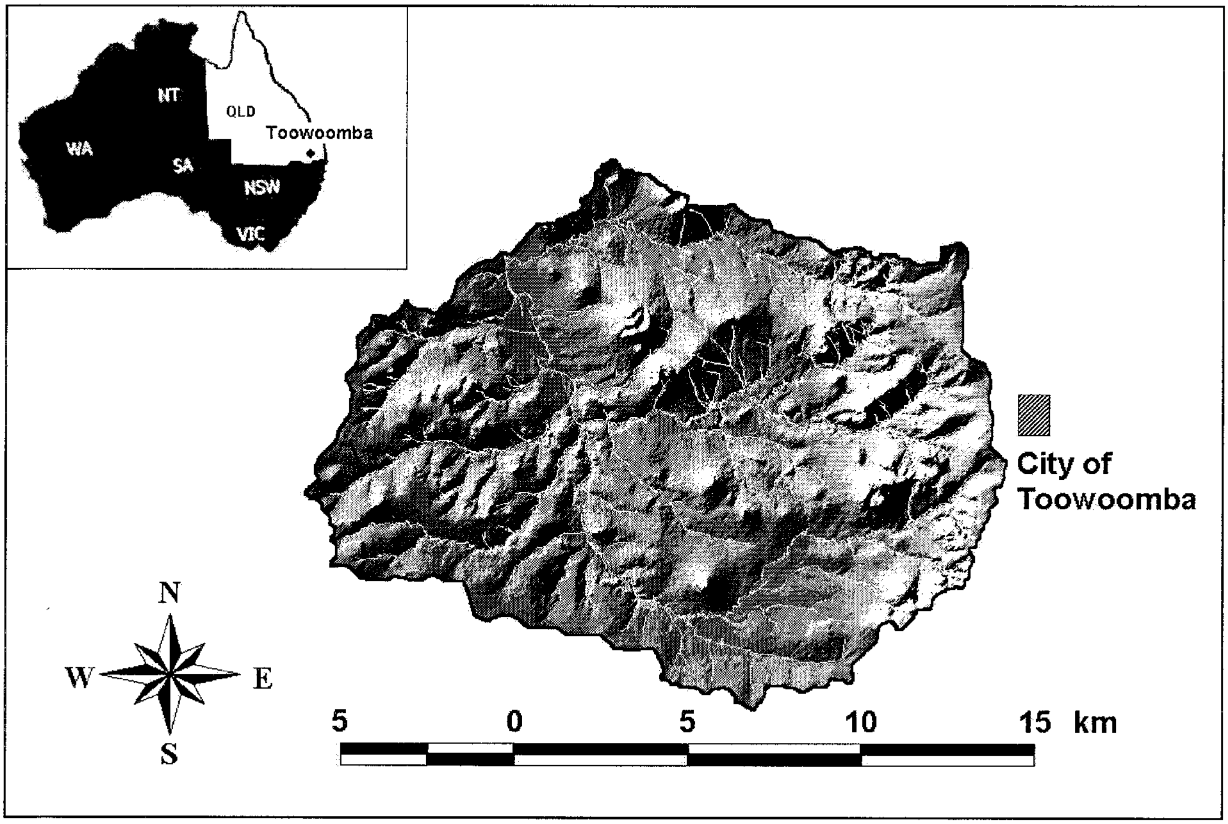

Figure 1. Study area: Westbrook subcatchment, southeast Queensland, Australia.

gree of agricultural site suitability for the application of animal waste, and (3) quantify the effect of the number of input factors, weights between factors, and the constraints imposed by the factors on the areal extent and the degree of site suitability.

Research Methods

Study Area

The study area covers the Westbrook subcatchment (Figure 1) in southeast Queensland, Australia. The 24,903-ha area of the subcatchment encompasses 20 dairies, 4 feedlots, 9 piggeries, and 6 poultry farms. The area is drained by the Westbrook Creek system and is relatively flat (i.e., 90% of the area within 10% slope) with undulating to rolling hills. Most of the flat and undulating areas with fertile self-mulching Vertisols are used for extensive farming. Other land uses and vegetation include native pasture, woodlands, and open forest. There are no major townships within the subcatchment but the city of Toowoomba adjoins the study area in the east.

Input Factors

Factors influencing the suitability of a site for the application of animal waste were selected by reviewing relevant information from the literature. The following examples illustrate the basis of factor selection. The soil type (permeability, texture, depth, pH) is considered important because it plays a vital role in retaining applied manure and supplying manure nutrients to the crops (Sutton and others 1999). Soil available phosphorus is also considered important to avoid excessive application of manure that can potentially lead to phosphorus runoff (Daniel and others 1994). Land cover and land use determine the extent of manure nutrient utilization and influence the nutrient runoff potential (Safely 1994). The ground slopes affect the runoff of the nutrients from the fields fertilized with animal waste (Safely 1994). The nutrients lost from the fields are more likely to end up in the watercourses (e.g., streams) if they are too close to the fertilized fields (Daniel and others 1994). Therefore, the inclusions of factors such as soil, soil fertility, land use, land cover, slope, and proximity to the streams are relevant in the

Table 1. Data acquisition: sources, formats, accuracy and uses[a]

Digital data	Source/format/accuracy	Purpose/use
Vegetation map for Murray Darling Basin (MDB)	DNR Queensland/ArcView Shape files/ digitized from 1:25,000	Derived land cover data layer by selecting crop and pasture area. Input to WLC model.
Cultivation map for southeast Queensland	DNR Queensland/ArcView Shape files/ digitized from 1:25,000	Derived land use map, which excluded the native pasture areas present in the land cover. Input to WLC model.
Statewide Land and Trees Study (SLATS) map for Queensland	DNR Queensland/ARC/INFO export file/digitized from 1:25,000	Derived residential (town) coverage. Input to WLC model.
Drainage network for southeast Queensland	NDR Queensland/ARC/INFO export file/digitized from 1:25,000	Derived stream network. Input to TOPOGRID; converted to proximity map; input to WLC model.
Digital contour data (topographic map)	DNR Queensland/ARC/INFO export file/10-meter contour interval	Used as an input in TOPOGRID (ARC/INFO) to derive digital elevation model (DEM)
Queensland state digital road network data	ERSIS Australia/Map INFO format/ 1:50,000	Derived proximity to road map. Input to WLC model.
CSIRO soils map for southeast Queensland	Marketed by DNR/ArcView Shape file/ digitized from 1:50,000	Used to derive fertility map in combination with the laboratory soil test information from the literature. Input to WLC model.
Intensive animal industries location maps	Collected by AgWise group, EDROC Inc./ArcView Shape file/scale: 1:25,000	Dairy, feedlot, piggery, and poultry location maps were combined to a single IAI layer before creating a proximity map. Input to WLC model.

[a]WLC: weighted linear combination; CSIRO: Commonwealth Scientific and Industrial Research Organisation, Australia; DPI: Department of Primary Industries, Queensland; DNR: Department of Natural Resources, Queensland; EDROC: Eastern Downs Regional Organisation of Councils, Queensland.

site selection process. Similarly, the economic significance of the animal waste application is dependent on the hauling costs from the IAI locations to the fields via transportation routes (Eghball and Power 1994). This justifies the inclusion of road and IAI factors in the analysis. The offensiveness of the odor generated from the application of animal waste decreases with the distance from residential areas (Safely 1994), which requires the use of a town factor in the selection process. Many research workers have commonly used most of these factors to select sites for different purposes. For example, Hendrix and Buckley (1992) identified land fill sites, He and Shi (1998) determined manure distribution sites, Jain and others (1995) sited animal industries, and Vorhauer and Hamlett (1996) sited farm ponds using factors such as soil, slope, land use, land cover, and proximity to streams. He and Shi (1998) also considered soil phosphorus content to identify suitable parcels of cropland for manure application. Siddiqui and others (1996) reviewed a landfill site selection procedure in which proximity to a population center is one of the most important factors. Similarly, Basagaoglu and others (1997) selected waste disposal sites by incorporating factors such as water, soil, topography, settlements, roads and ecological features.

Data Acquisition and Preprocessing

Point (location of intensive animal industries), line (contour, stream, and road network maps), and polygon (soil, land use, land cover, and cadastral maps) data sets were acquired for the study area from various sources in different data formats (Table 1). Only the data sets derived from large-scale maps (i.e., 1:25,000 rather than 1:100,000) were selected.

The flow chart showing the input grid preparation process is given in Figure 2. Preprocessing included importing, edge matching, editing, correcting, projecting, cleaning, and topology building. This preprocessing was conducted using ARC/INFO (ESRI 1992) prior to converting vector coverages into raster grids.

A digital elevation model (DEM) was prepared using contour- and flow-corrected stream coverages as inputs in TOPOGRID, which is a DEM building module built-in within ARC/INFO program. To improve accuracy, the DEM was made depressionless by filling sinks. Slope, flow direction, and flow accumulation themes

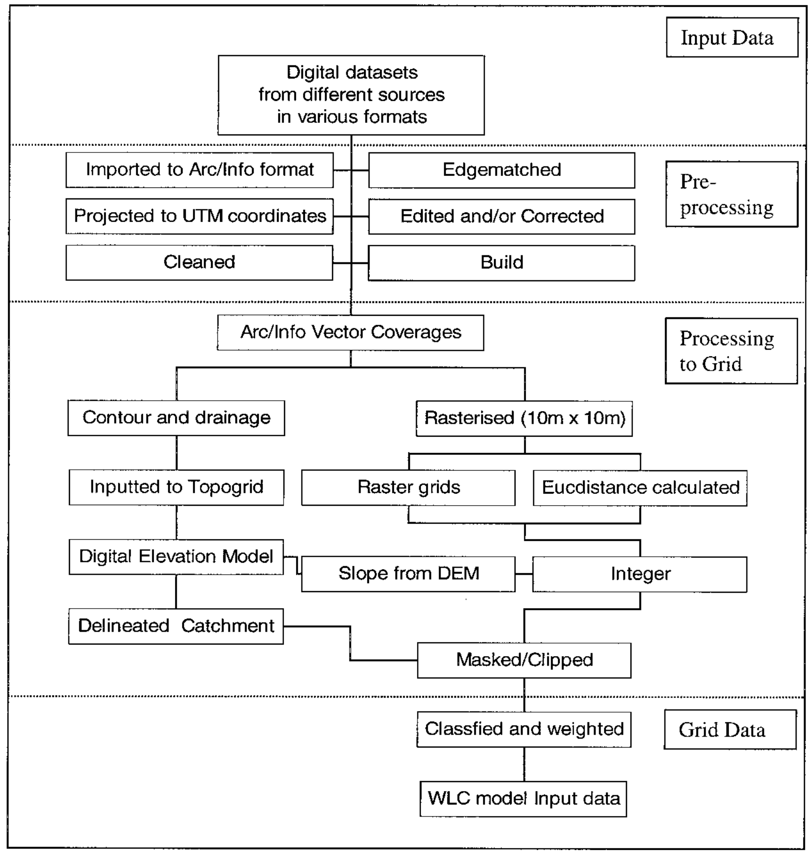

Figure 2. Data sets and preprocessing for selecting sites suitable for animal waste application.

were derived from the DEM. The catchment boundary was delineated from the flow direction grid using flow accumulation and stream coverage as a guide to locate the outlet.

All vector coverages (soil, land cover, land use, stream, town, fertility, and road) were converted to grids (rasterized) of 10-m × 10-m cell resolutions (Figure 2), which was considered small enough to display required details (e.g., ground slope, land cover, IAI locations) sufficiently. Rasterization was necessary to make use of the ARC/INFO GRID module that allows weighted linear combination modeling. Dairy, feedlot, piggery, and poultry map layers (Table 1) were merged into a single IAI grid. Residential (town) areas were derived from the SLATS (State-wide Land Cover and Trees Study) data as a separate map layer. Available soil phosphorus data (Thompson and Beckmann 1959) were used to derive a soil fertility map by recoding soil map layer. Euclidean distances were calculated for each of the stream, road, town, and IAI data layers to enable the classification and rating of the factors by distance. Each of the grids, including slope, was clipped using the delineated catchment boundary and the floating-point grids converted to integer to make the attribute tables available for reclassification and scoring.

Reclassification

The input factors were categorized into nine biophysical, environmental, and socioeconomic parameters. Areas considered totally unsuitable for animal waste application were identified and excluded from each of the input factor (Table 2). For example, areas with slopes greater than 10% are considered unsuitable for land application of waste (NSW Agriculture and Fisheries 1989) and therefore are blacked out from the slope data layer.

The remaining factor attributes were classified into five classes for each factor (Table 3). Classification was based on the data range, data type, and data distribution. For example, a single class in the land cover factor was due to lack of appropriately categorized data. Whenever possible, discrete data (e.g., soil type, soil fertility) were classified following the natural (existing) boundaries.

Weight Distribution Within and Between Factors

Factor attribute classes were weighted using the pairwise comparison module (i.e., WEIGHT), which is a built-in function in the IDRISI software (Eastman 1997). Numeric scores to a total of one (zero as least

Table 2. Guidelines for imposing constraints to input factors used in determining site suitability for animal waste application

Selected category	Relevant information from the literature
Crop/pasture (land cover)	Land cover contained areas such as wood land, forest, and settlement that are not suited for animal waste application.
Cultivated land (land use)	Land use included both cultivated and uncultivated areas. Application of animal waste is confined to cultivated area only.
Buffer zone 250 m (proximity to town[a])	A buffer strip of 500 m from residential area is recommended for land application of sewage sludge (NSW Agriculture and Fishery 1989). Use of animal waste as manure is socially more acceptable.
Buffer zone 100 m (proximity to stream)	A buffer strip of at least 100 m from surface water (eg. streams, lakes) must be maintained for the land application of animal waste (He and Shi 1998) and sewage sludge (NSW Agriculture and Fishery 1989).
Very shallow and stony soil not included (soil factor)	The buffering capacity of a soil depends on soil pH, organic matter content and cation exchange capacity that are related to soil texture (NSW Agriculture and Fishery 1989)). Some naturally infertile very shallow, stony soil may have very little buffering capacity and high runoff.
Areas below 10% slope selected (slope factor)	Sludge should not be used on ground with more than 10% slope (NSW Agriculture and Fishery 1989). Use of animal waste should be limited to the ground slope of ≤6%, (He and Shi 1998).
Area beyond 25m (road factor[b])	Minimum buffer width from farm roads and fence lines for sludge application is 20 m (NSW Agriculture and Fishery 1989).
Areas within 100 m from IAI excluded	Waste is generated but not applied within the intensive animal industries (IAI). A buffer distance of 100 m was set after visiting intensive animal production facilities.
No area excluded from fertility; available P did not exceed 1200 ppm	Application of animal waste must consider soil nutrients. Nutrient loading should be based on P in areas with P sensitive water bodies and on N where eutrophication is not a problem (Moore and others 1995). Manure should not be applied for crop production purposes when soil P level exceeds 1504 ppm (Johnson and Eckert 1995).

[a]Halved the buffer distance because animal waste is socially more acceptable than the sludge.

[b]Minimum road buffer is 20 m, but 25 m selected due to presence of major road network.

and one as most suitable) were assigned to each factor attribute class (Table 3). Comparisons between classes were based on their level of suitability with respect to animal waste application. A pairwise comparison matrix was formulated using the results of previous studies (e.g., Siddiqui 1996, Banai-Kashani 1989) as a guide. A consistency ratio of less than 0.05 was maintained throughout the weight derivation process, indicating that the weight determination matrix was acceptable (Eastman 1997). Weights were transferred to the value attribute table (VAT) of the respective grids as a separate item.

Factors were weighted against each other in terms of their contributions towards the biophysical, socioeconomic and environmental aspects of the animal waste application in agricultural fields. Weights between factors were distributed using pairwise comparison method developed by Saaty (Eastman 1997) in the context of a decision-making process known as the analytical hierarchy process (AHP). The AHP statistically computes the distribution of weights from a given set of relative importance ranking (Banai-Kashani 1989). The relative importance ranking of input factors was determined by making an objectives-oriented comparison (OOC) that required valuing each factor in terms of achieving the desired objectives of the site suitability analysis (Table 4). The OOC method has been developed by the authors to make factor-weighting process logical and systematic. The objectives and scores for the OOC were identified via interview with a panel that included representatives of catchment stakeholders (e.g., farmers, local shire councils, government department, and university). The total score obtained from the OOC for each factor was then used as ratios in the AHP-based pairwise comparison matrix that calculated the eigenvector of weights for each input factor (Table 5). The benefit of using AHP, as opposed to direct calculation of weight using OOC (Table 4), is its ability to calculate the consistency ratio of weight distribution and its consequent evaluation of the weighting process (Eastman 1997). The AHP also maintains the factor weights sum to one, which is a requirement

Table 3. Classification and weighting of factor attribute classes used in assessing site suitability for animal waste application

Factors		Classification and weight distribution					
Bio-physical							
Fertility available P (ppm)	Weight		0.5146	0.2487	0.1247	0.0649	0.0471
	Class		0–100	101–350	351–700	701–1000	1001–1504
Land cover	Weight	Null			1.0000		
	Class	Others			Crops and pasture land		
Soil type[a]	Weight	Null	0.0471	0.0649	0.1247	0.2487	0.5146
	Class	Shallow	Poor	Medium	Good	Better	Best
Slope (%)	Weight	Null	0.0333	0.0634	0.1290	0.2615	0.5128
	Class	>10%	8–10	6–8	4–6	2–4	0–2
Environmental							
Proximity to stream (m)	Weight	Null	0.0333	0.0634	0.1290	0.2615	0.5128
	Class	0–100	101–250	251–500	501–750	751–1000	>1000
Proximity to IAI[b] (m)	Weight	Null	0.2505	0.2214	0.1972	0.1756	0.1553
	Class	0–100	101–1500	1501–3000	3001–4500	4501–6000	>6000
Socioeconomic							
Land use	Weight	Null			1.0000		
	Class	Others			Cultivated land		
Proximity to road (m)	Weight	Null	0.2505	0.2214	0.1972	0.1756	0.1553
	Class	0–25	26–500	501–1000	1001–1500	1501–2000	>2000
Proximity to towns (m)	Weight	Null	0.0333	0.0634	0.1290	0.2615	0.5128
	Class	0–250	251–750	751–1250	1251–1750	1751–2250	>2250

[a]Soil factor classified by ranking properties (e.g., depth, texture, permeability, and pH).

[b]IAI: intensive animal industries; Null: no weighting to the eliminated areas that are totally unsuitable for waste application.

Table 4. Determination of relative importance of input factors using an objectives-oriented comparison (OOC) matrix

Input factors	Objectives[a] A	B	C	D	E	F	G	H	I	Total value	Direct calculation of weight
Land cover	½	½	0	1	½	0	1	0	0	3½	3½/27 = 0.1296
Land use	½	½	½	1	½	0	1	0	½	3½	3½/27 = 0.1296
Proximity to town	0	0	0	0	0	0	0	0	1	1	1/27 = 0.0370
Proximity to stream	1	0	0	0	0	0	0	0	0	1	1/27 = 0.0370
Soil	½	½	1	1	1	0	1	0	0	5	5/27 = 0.1852
Slope	1	½	0	1	½	0	0	0	0	3	3/27 = 0.1112
Proximity to road	0	0	0	0	0	0	0	1	0	1	1/27 = 0.0370
Proximity to IAI	1	0	0	0	0	1	0	1	1	4	4/27 = 0.1482
Soil fertility	½	½	1	1	½	1	½	0	0	5	5/27 = 0.1852
Total										27	Σweight = 1.00

[a]Contribution of input factors in terms of A: reducing surface water pollution, B: reducing ground water pollution, C: reducing soil contamination, D: reducing runoff loss of nutrients, E: reducing leaching loss of nutrients, F: avoiding excessive use of manure, G: increasing nutrient use efficiency, H: reducing cost of manure application, I: reducing air pollution (bad odor). 0: no contribution, ½: partial contribution, 1: full contribution.

in using the weighted linear combination procedure (Eastmann 1997, Kuiper 1999).

Site suitability was calculated using the ARC/INFO GRID module (ESRI 1992) and the following weighted linear combination:

$$S_i = \sum_{j=1}^{n} (f_{ji}.suit \times w_j) \qquad (1)$$

where S_i is the suitability value for each cell location f_{ji}.. suit is the grid dot notation for class in VAT (from Table 3); and w_j is the respective weight for factor f_j (from Table 5).

Calculated suitability values were classified into areas of high, medium, and low suitability using the natural break method available within the ArcView GIS software. This method identifies natural breakpoints by

Table 5. Weight distribution between factors using an analytical hierarchy process-based pair-wise comparison matrix[a]

Pair-wise comparison matrix derived using OOC scores as ratios										
Factors	Land cover	Land use	Town	Stream	Soil	Slope	Road	IAI	Fertility	AHP weight distribution between input factors[b]
L/cover	1									0.1291
L/use	1	1								0.1291
Town	1/3½	1/3½	1							0.0372
Stream	1/3½	1/3½	1	1						0.0372
Soil	5/3½	5/3½	5	5	1					0.1854
Slope	3/3½	3/3½	3	3	3/5	1				0.1114
Road	1/3½	1/3½	1	1	1/5	1/3	1			0.0371
IAI[a]	4/3½	4/3½	4	4	4/5	4/3	4	1		0.1481
Fertility	4/3½	4/3½	5	5	1	5/3	5	5/4	1	0.1854

[a]IAI: intensive animal industries.

[b]Consistency ratio of weight distribution = 0.00 (consistency is acceptable).

looking for groupings and patterns inherent in the data (ESRI 1996). Weighted average, weighted standard deviation, and coefficient of variation of the suitability values were calculated to infer central tendency and the overall degree of suitability.

A sensitivity analysis was conducted to verify the effect of the number of input factors on the total area identified as suitable and the degree of suitability. Factors were ordered based on potentially available area before processing them using the WLC model. In this analysis, all the input factors were assigned the same weight and no changes were made to the factor attribute classes and weights. However, variations in the number of input factors produce output grids with different ranges of suitability values that are not readily comparable. Thus, appropriate multipliers were used to convert the suitability values to comparable ranges to evaluate the effects of varying the number of input factors (e.g., $45 \times \{f_1.\text{suit} + f_2\ \text{suit}\}$, or $30 \times \{f_1.\text{suit} + f_2\ \text{suit} + f_3\ \text{suit}\}$, or $10 \times \{f_1.\text{suit} + \ldots + f_9\ \text{suit}\}$). A multiplier of 10 was arbitrarily selected to amplify the WLC model output of nine factors.

The effect of weight distribution between factors on the areal extent and the degree of suitability were also examined. Tests were conducted by assigning a higher weight to one input factor at a time. Nine input factors were used and the classes within each factor were left unchanged.

Results

The areas suitable for animal waste application in the Westbrook subcatchment and their degree of suitability were mapped (Figure 3) and the results summarized in Table 6. Most input factors contained some areas that are essentially unsuitable for animal waste application (e.g., too close to watercourses, residential area, or too steep). Exclusion of such areas has effectively reduced the potentially available areas in the respective input factors (Table 7).

Increasing the number of input factors in the order presented in Table 7 effectively reduced the areal extent and the degree of site suitability (Table 8). In this instance, the reduction in the areal extent of site suitability was affected by all input factors except soil fertility (Table 8). A significant reduction in the total suitable area was caused by the inclusion of input factors with severe areal constraints (e.g., land cover, land use, towns, and streams).

As would be expected, the AHP weight distribution between factors had no effect on the areal extent of site suitability (Table 9). However, weight distribution did have a substantial effect on the degree of suitability as indicated by cell value range, weighted average, and coefficient of variation (Table 9). The average cell value obtained using the factor weights derived from the OOC scores (Table 5) was 35.8 (SD = 2.9, CV = 8.1%, and value range = 22).

Discussion

The weighted linear combination model of site selection implemented in this study identified 16.2% of the subcatchment area as suitable for animal waste application (Table 6). This relatively small percentage of total area available for animal waste application is attributed to

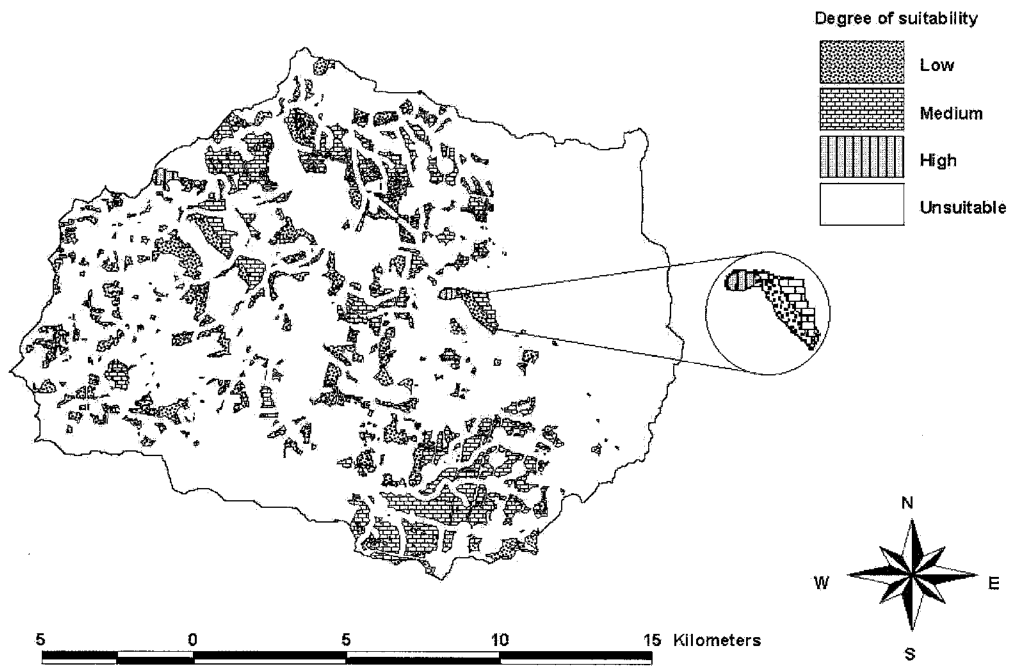

Figure 3. Degree of site suitability for animal waste application in the Westbrook subcatchment, southeast Queensland.

Table 6. Summary of site suitability analysis for application of animal waste in Westbrook subcatchment

	Area	Degree of suitability[a]			Range of cell value[b]	Average cell value
		Low	Medium	High		
Suitable (ha)	4043	1708	2248	87	22	35.83
Suitable (%)	16.23	6.86	9.02	0.35	(30–52)	(±2.9)
Unsuitable (ha)	20860					
Total (ha)	24903					

[a]Cell values classified using natural break function.

[b]Maximum possible value = 90.

the presence of a large proportion of residential, nonagricultural, and noncultivated land use in the Westbrook subcatchment. This is clearly evidenced from the fact that the combined factors of land cover and land use alone eliminated 67% of the total catchment area (Table 8). The limited area identified as suitable for waste application and the number of intensive animal industries (39) already present in the subcatchment suggests that there is a pressing need to assess the capacity of the subcatchment to fully absorb the generated waste. If necessary, other nearby subcatchments with fewer intensive animal industries could be considered as potential recipients of excessive animal waste.

Areal Extent of Suitability

Factors are data layers or themes with unique characteristics (e.g., soil, slope, and land use). Diversity of attributes within a factor is natural and may contain areas suitable and/or unsuitable for a specific purpose. All other factors, except soil fertility, contained areas that were classified as unsuitable for animal waste application and eliminated (Table 7). Deriving a suitability map using a weighted linear combination model results in a product matrix. This implies that the input of a factor with some eliminated areas (i.e., black hole) results in that area being removed (i.e., blacked out) in the product matrix. Incorporating more of such factors in the WLC model would therefore decrease the areal extent of suitability. The magnitude of unsuitable areas in each input factor would proportionally decrease the areal extent of suitability if such areas were mutually exclusive in each input factor. However, due to the overlap of totally unsuitable areas between input factors, the result presented in Table 8 demonstrates a

Table 7. Effects of exclusionary criteria on area potentially available for animal waste application in each input factor

No.	Input factors	Exclusionary criteria imposed on input factors	Potentially available area ha	%
1	Land cover	Crop and pasture areas (all other areas excluded).	10,720	43.0
2	Land use	Cultivated area (noncultivated areas excluded).	11,936	47.9
3	Town	Areas within 250 m of residential areas excluded	17,387	69.8
4	Stream	Areas within 100 m of either side of the streams not included.	17,833	71.6
5	Soil	Very shallow, stony, clay loam soil not included.	19,009	76.3
6	Slope	Ground areas with slope greater than 10% excluded.	22,451	90.1
7	Road	Areas within 25 m of either side of the road excluded.	23,116	92.8
8	IAI	Areas within 100 m radius of IAI location excluded.	24,783	99.5
9	Soil fertility	No exclusion. All the area considered potentially available.	24,903	100.0
Total subcatchment area (ha)			24,903	

Table 8. Effect of number of factors included in analysis on areal extent and degree of site suitability

Factors added (N)	Factors included in analysis[a] (factors with least potentially available area first: refer Table 7)	Suitable areal ha	%	Degree of suitability[b] Weighted average[b]	Weighted SD	CV (%)
2	Land cover and land use	8208	32.96	90.00	0.00	0.00
3	Plus proximity to town	6736	27.05	62.05	2.06	3.32
4	Plus proximity to stream	4835	19.41	47.69	1.80	3.77
5	Plus soil	4161	16.71	40.88	2.07	5.06
6	Plus percent slope	4147	16.65	39.33	3.07	7.81
7	Plus proximity to road	4054	16.28	36.75	2.63	7.15
8	Plus proximity to IAI	4043	16.23	34.85	2.27	6.53
9	Plus soil fertility	4043	16.23	32.31	2.23	6.91

[a]Using descriptive statistics.

[b]Maximum possible value = 90.

continuous but not proportional decrease in the areal extent of suitability. Note that the weight distribution between factors does not affect the areal extent of site suitability (Table 9) because the weight distribution process only assigns higher or lower values to the available area in each input factor. Clearly, weighting of input factors is not a requirement if the purpose is only to determine the areal extent of suitability.

The limited potentially available area associated with the first few input factors (Table 7) had a significant effect on the total suitable area. An 83% drop in suitable area was caused by overlaying the first five input factors (Table 8) in the order presented in Table 7. Changing this order may alter the suitability outcome, however, using the most constricting factors first is not only logical and efficient but also helps in identifying the most critical factors. The soil fertility input factor, with the entire area available for animal waste application, had no effect on the areal extent of suitability (Table 8). It seems reasonable to conclude that in this example, the minimum number of input factors required for site suitability assessment is either four (for greater than 97% accuracy) or five (for more than 99% accuracy). Generalization is not possible for other situations as it seems that the number of factors required for an areal extent of suitability assessment will be dependent on the degree of overlap between each input parameter. However, the general principle is that the inclusion of those factors with the largest excluded areal extent and lowest level of overlap between the excluded areas would result in the most rapid delineation of suitable areas by the successive input of each layer.

Degree of Suitability

The degree of site suitability is a function of the range and frequency of cell values in the product matrix. The degree of suitability has been evaluated

Table 9. Effect of weight distribution on areal extent and degree of suitability

Input		Output				
			Degree of suitability[a]			
Factor assigned 52.96% weight	Weight assigned to all other factors	Suitable area (ha)	Range of cell values	Weighted average of values[b]	Weighted standard deviation	Coefficient of variation (%)
Land cover	5.88% each	4043	10	59.47	1.22	2.04
Land use		4043	10	59.47	1.22	2.04
Slope		4043	30	32.00	7.50	23.43
IAI		4043	12	27.31	1.33	4.87
Road		4043	13	27.15	1.46	5.37
Soil		4043	30	23.32	4.18	17.92
Fertility		4043	29	22.68	4.90	21.59
Towns		4043	26	19.89	2.96	14.86
Stream		4043	30	19.67	2.43	12.35

[a]Using descriptive statistics.

[b]Maximum possible value = 90.

(Table 6) by classifying output cell values into low, medium, and high categories using the natural break function available in ArcView GIS and by calculating central tendency statistically. Natural break and other similar classification methods (e.g., equal area and equal interval) categorize data into various suitability classes (e.g., low, medium, and high) by looking at the pattern of individual data sets. However, this type of classification does not enable the direct comparison of results because of the likelihood of varying patterns in individual data sets. Reporting the central tendency as the weighted average, weighted standard deviation, and coefficient of variation may provide a more appropriate measure if the degree of suitability of many data sets (outputs) is to be compared (Table 8 and 9). When classified using natural break function, 6.8%, 9.0%, and 0.4% areas were of low, medium, and high degree of suitability, respectively (Table 6). However, irrespective of the analysis techniques, it is obvious that some areas are better suited for animal waste application than others (Figure 3). Information of this nature is valuable in providing decision support for the site-specific application of animal waste in the agricultural fields.

Input factors with a single suitability class, such as land cover and land use (Table 3) excluded unsuitable areas but did not discriminate the remaining areas by the level of suitability. Most input factors, however, are not spatially homogeneous. They contain both unsuitable areas as well as areas with different levels of suitability (Table 3). Increasing the number of such input factors has resulted in the reduction of the overall degree of suitability as indicated by the decreasing weighted average (i.e., mean cell value) and generally increasing the coefficient of variation (Table 8). This suggests that increasing the number of input factors with multiple attribute classes reduces the degree of suitability and the area potentially classified as highly suitable. This is presumably due to the split of weight between classes. However, there is a need to further examine the effect of the number of factor attribute classes and the weight distribution between classes to fully understand the implication for suitability classification.

The weight distribution between factors also significantly affected the degree of suitability (Table 9). Assigning higher weights to some input factors (e.g., streams, towns, and soil) resulted in a much lower weighted average (Table 9), indicating far greater impacts of these factors on the degree of site suitability. This may suggest that these are the most constricting factors in terms of suitability for animal waste application. The coefficient of variation is highly variable depending on the factor most heavily weighted (Table 9). This variability is most likely associated with the variation in the area excluded within each input factor but further research is required to adequately explain this effect.

One major difficulty of factor weighting is the weight distribution between factors. Weight distribution is unavoidable because factors contribute differently to the degree of site suitability. However, determining the weights for input factors is often arbitrary and subjective. Typically, factor weights are determined through the consensus of an expert panel. However, the availability of expert knowledge is limited and consensus is often difficult to achieve (Lowry and others 1995). An objective oriented comparison method (Table 4) introduced in this work formalized the weighting process by urging the expert panel to focus specifically on the effect of each input factor on individual objectives. This is a systematic and logical technique that may reduce weighting inconstancies and improve consensus. However, the expert knowledge is still essential to formulate the objectives and to quantify the contribution of each input factors in terms of fulfilling those objectives (Table 4).

Conclusion

The raster GIS-based weighted linear combination model has been used in this study to identify, rank, and map cultivated agricultural areas potentially suitable for animal waste application in the Westbrook subcatchment. In this context 16.2% of the subcatchment area was found suitable for animal waste application. The site suitability map shows promise for the safe application of animal waste in agricultural fields and may be a potentially valuable guide for animal producers, farmers, agriculturists, environmentalists, and licensing officers.

The degree of suitability values ranged between 30 and 52 on a scale of 0–90. When classified using natural break function, the areas of low, medium, and high degrees of suitability were in a 17:23:1 ratio. The degree of suitability measurements may serve as a valuable guide to adjust the rate and frequency of manure application and to improve (or alter) the management practices.

An understanding of the GIS-based weighted linear combination model for site selection was developed through the evaluation of the effects of input factors and their weighting on the areal extent and the degree of site suitability. Increasing the number of input factors with largest areal constraints (excluded areas) caused rapid reduction in total suitable area. The magnitude of excluded areas in each input factor affected the areal extent and the degree of site suitability. Weight distribution between factors significantly affected the degree of suitability.

Weighting of factors using the analytical hierarchy process (AHP) required expert knowledge and a consensus. The objectives-oriented comparison (OOC) method introduced in this work formalized the weighting process by urging the expert to focus on objectives that potentially can reduce inconstancies and improve consensus. This study has also highlighted the influences of the number of factor attribute classes and the weight distribution between classes on the degree of site suitability that require further investigation.

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